Workshop Highlights and Summary[1]

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INTRODUCTION

The acceleration of polarized proton beams with energies in the range of 3 - 30 GeV in circular accelerators is very challenging since depolarizing resonances are strong enough to cause significant if not complete depolarization but the beam energy is too low for practical designs of full Siberian snakes. Over the last thirty years, however, several techniques have been developed to overcome depolarizing resonances with significant success.

During this workshop the experience and new methods of accelerating polarized beams in circular accelerators were presented and discussed with the goal of planning a strategy to raise the beam polarization in the Brookhaven Alternating Gradient Synchrotron (AGS) to the highest possible level. The AGS serves as injector to the 500 GeV polarized proton collider RHIC. The planned two-spin experiments at RHIC are very sensitive to the level of polarization both for improved experimental statistics and reduced systematic errors.

For low-energy, rapid-cycling machines such as the AGS, only first-order depolarizing resonances are important. The resonance condition for the spin tune ν_{sp} is:

$$\nu_{sp} = G\gamma = n \pm m\nu_y \pm k\nu_x \quad (m,k = \{0,1\})$$

There are two main types of first order depolarizing spin resonances: imperfection resonances, which are driven by magnet errors and misalignments, and intrinsic resonances, driven by the focusing fields. The strengths of both types of resonances increases with beam energy. The intrinsic resonances themselves can be grouped into three categories: strong intrinsic resonances that lead to complete depolarization or partial spin flip; weak intrinsic resonances that cause some depolarization; and coupling resonances that are driven by the horizontal betatron motion coupled into the vertical plane by skew quadrupoles or solenoids.

During acceleration in the AGS to RHIC injection energy 42 imperfection resonances, 4 strong and 3 weak intrinsic resonances, and 4 coupling resonances are crossed. Each resonance can cause significant beam depolarization. The level of expected depolariza-

[1] Work performed under the auspices of the U.S. Department of Energy

tion or spin flip is given by the Froissart-Stora formula:

$$P_f/P_i = 2e^{-\frac{\pi|\varepsilon|^2}{2\alpha}} - 1,$$

where P_i and P_f are the polarizations before and after the resonance crossing, respectively, ε is the resonance strength, and α is the ramping speed. If the beam is accelerated through the resonance slowly or the resonance is very strong ($\alpha \ll |\varepsilon|^2$), the spin vector will adiabatically follow the stable spin direction resulting in complete spin flip. For fast acceleration or weak resonances ($\alpha \gg |\varepsilon|^2$)the polarization remains unchanged. However, for intermediate conditions partial depolarization or partial spin flip will occur.

The methods developed to overcome depolarization can then be grouped into "adiabatic methods", where the resonance strength is increased or the ramp rate decreased to achieve full spin-flip, and "non-adiabatic methods" where the resonance strength is reduced or the ramp rate increased until no polarization is lost. Examples of the former are the use of a localized spin rotator or 'partial Siberian snake' to make all the imperfection resonance strengths large and the use of a vertical rf dipole magnet to create a strong artificial spin resonance, overpowering the effect of the intrinsic resonances. The "non-adiabatic methods" were used early on and consist of the use of correction dipoles to minimize the strength of imperfection resonances and pulsed quadrupoles to jump the betatron tune during intrinsic resonance crossing, which increases the effective ramping speed.

EXPERIENCE AT EXISTING FACILITIES

Table 1 shows a compilation of the methods used at the three machines represented at this workshop. Also listed are the type of polarimeters used to measure the circulating beam polarization and what information was used to set-up the machine. Typically the beam polarization is measured at the end of the acceleration cycle. Using this information for machine set-up can be quite time-consuming and also makes it very difficult to diagnose depolarization from crossing a resonance during acceleration. Polarization measurement during the acceleration ramp makes this easier but typically takes a long time and also causes emittance growth that can itself lead to depolarization. The adiabatic methods allow at least the initial set-up to be performed using beam information which is easily available during the acceleration ramp.

Andreas Lehrach summarized the experience from the Cooler Synchrotron (COSY) in Juelich, Germany. Pulsed quadrupoles are used to overcome the intrinsic resonances and harmonic orbit correction dipoles are exited enough to cause full spin flip. Using the corrector dipoles to enhance instead of correcting the imperfection resonance strength requires a large aperture but is operationally more stable. The maximum energy reached is $G\gamma \approx 7$ with about 75 % polarization. The performance is presently limited due the marginal size of the tune jump for the strongest intrinsic resonances. It was also successfully demonstrated that proper modifications to the lattice (spin matching) can suppress the strength of individual weak intrinsic resonances. This method works well if the machine lattice has sufficient built-in flexibility.

The KEK Proton Synchrotron accelerated polarized protons during the 1980's and reached about 40% polarization at $G\gamma = 8.4$ and 25% at $G\gamma = 11.2$, as reported by Chihiro Ohmori. KEK used correction dipoles and pulsed quadrupoles to overcome intrinsic and imperfection resonances. The experience also showed that the tune jump was too small for the very strong intrinsic resonances of the KEK PS.

Leif Ahrens summarized the first experience of accelerating polarized protons at the Brookhaven AGS. During this first effort the non-adiabatic methods that were later used at KEK and COSY were developed. The 94 corrector dipoles were successfully used to overcome imperfection resonances although operationally the set-up and maintenance of the correct tuning of these many dipoles was quite time consuming. A very powerful, pulsed quadrupole system worked very well to overcome the intrinsic resonances and, after careful alignment, did not substantially increase the beam emittance. The strength of both the corrector dipoles and the tune jump system became marginal at the highest AGS energies. The maximum polarization reached was about 45% at $G\gamma = 41.5$.

Haixin Huang and Mei Bai reported on the recent efforts to accelerate polarized protons in the AGS for injection into RHIC. A partial Siberian snake is used to enhance the strength of all imperfection resonances and a vertical rf dipole magnet creates a strong artificial spin resonance by driving large coherent betatron oscillations, overpowering the effect of the intrinsic resonances. Both of these methods are adiabatic which makes them operationally more stable and also allows the set-up to be performed using beam information instead of the polarization information which takes a long time to acquire. Also both the partial Siberian snake and the rf dipole method are able to deal with very strong resonances. However, the three weak intrinsic resonances and the four weak coupling resonances generated by the partial snake solenoid cannot be treated by the vertical rf dipole method. Nevertheless, a polarization of about 40% was reached at the RHIC injection energy of $G\gamma = 46.5$.

ADDITIONAL METHODS AND PLANS

An alternative method, described by Haixin Huang, was recently tested at the AGS. With a strong enough partial Siberian snake both imperfection and intrinsic resonances can be overcome. The minimum strength is about 20% of a full snake and it also requires that the betatron tune is brought very close to an integer value which makes machine operation less stable. This method is analogous to the operation with a full Siberian snake with the main advantage that with a single device depolarization from all types of resonances can be avoided.

Based on the presented experience and discussions preferred methods for each type of depolarizing resonance are summarized in Table 1 under Plan 1. Plan 2 consists of a strong 25% partial Siberian snake that can cope with all resonances. Imperfection resonances are well treated with a partial Siberian snake. Coupling resonances are best avoided by building a partial snake that does not introduce orbit coupling. This can be accomplished using a helical dipole instead of a solenoid. Using the super-conducting magnet technology developed for the RHIC Siberian snakes a 20 - 30% partial snake can be build for the AGS. The same design produces a 5% partial snake if built as a warm

TABLE 1. Methods to overcome depolarizing spin resonances

	Imperfection resonances	Strong intrinsic resonances	Weak intrinsic resonances	Coupl. intr. resonances	Set-up information	Polarimeter	Meas. duration
COSY	corr. dipoles	pulsed quadrupoles	pulsed quadrupoles	N/A	Pol.	pC quasi-elast.	5 min.
KEK PS	corr. dipoles	pulsed quadrupoles	pulsed quadrupoles	N/A	Pol.	pC & pp elastic	2 min.
AGS (1983-1988)	94 corr. dipoles	10 puls. quadrupoles	10 puls. quadrupoles	N/A	Pol.	pC & pp elastic	10 min.
AGS (1994-2002)	5% solenoid snake	vertical rf dipole	Did nothing	Did nothing	Beam/Pol.	pC & pp elastic	10 min.
Plan 1	5% helical snake	vertical rf dipole	Intr. spin matching pulsed quadrupoles	N/A	Beam/Pol.	pC CNI	5 sec.
Plan 2	25% helical snake	25% helical snake	25% helical snake	N/A	Beam	pC CNI	5 sec.

magnet.

For weak intrinsic resonances there are several successful methods: a tune jump using pulsed quadrupoles has been demonstrated to work well, spin matching also works if the lattice is flexible enough, and a strong partial snake is expected to work as well. For strong intrinsic resonances, only the vertical rf dipole method has been demonstrated to be able to avoid depolarization although the accuracy of the experimental data still allows for a residual depolarization of a few percent. Proper set-up of the rf dipole requires very accurate tune control and a very small betatron tune spread, which is particularly difficult at higher beam intensities. For the strong intrinsic resonances the strong partial Siberian snake should eventually provide a better and operationally more stable solution.

SUMMARY

Based on this workshop a plan for upgrading polarized proton acceleration in the AGS was developed. The construction of a strong partial Siberian snake was initiated. Although in principle this single device would avoid all sources of depolarization in the AGS its construction, installation and commissioning will take several years. Also mismatch of the polarization direction at injection into the AGS will cause some depolarization. Plan 1 outlined above will be pursued in the meantime. A warm helical partial Siberian snake will replace the present solenoid snake. It will avoid the coupling resonances and can also be used in the future to avoid injection mismatch with the strong partial snake. Existing quadrupoles will be moved to locations where they can be used to suppress the weak intrinsic resonances as discussed at this workshop by Andreas Lehrach. This approach should give maximum polarization from the AGS as soon as possible and also provide a long term solution that is operationally simple and offers additional polarization improvements if the rf dipole method shows residual depolarization.